ASSESSMENT OF PERMAFROST CONDITIONS AT SALLUIT, NUNAVIK, USING CONE PENETRATION TESTS

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ABSTRACT
A geotechnical investigation was performed in Salluit in Nunavik (Canada) for assessing the permafrost conditions and delineating the available terrain to accommodate the village expansion on stable ground in permafrost despite the climate warming predicted for the next century. Penetration-rate controlled CPTs were carried out in permafrost at temperatures as low as -5 °C for stratigraphic profiling and studying the creep behaviour of permafrost. Ice-rich permafrost near the permafrost table in frost-susceptible marine sediments and colluvium, and saline ice-poor permafrost with few thick lenses of segregated ice in the marine sediments at depths larger than 2 m were investigated. The till in depth overlaid by the marine sediments was also penetrated over several centimetres during one CPT. The typical rate of penetration used for the CPTs was 0.1 cm/s; it is a good compromise between the very high values of cone resistance expected for permafrost at a standard rate of 2 cm/s due to the creep behaviour of permafrost, on one side, and the lower values of cone resistance and the very long time needed for performing deep CTPs at a rate of 0.1 cm/s, on the other side. The ice-rich permafrost and the ice lenses are characterized by cone resistance in excess of 20 MPa and friction ratio lower than 1% while the ice-poor saline permafrost has cone resistance close to 20 MPa and friction ratio higher than 1%. Cone resistance higher than 90 MPa at a rate of penetration of 0.01 cm/s were measured in the frozen till. This very low rate of penetration was used for decreasing the tip load and avoiding thus any damages to the pushing system and penetrometer. The creep exponents found from the creep tests are equal to 5 for the ice-rich permafrost and higher than 5 for the saline ice-poor permafrost. The variation in ice content can explain the difference in creep behaviour of permafrost. The cone penetration test is a useful geotechnical tool to assess the cryostratigraphy and creep behaviour of permafrost for designing foundations in a permafrost environment sensitive to climate warming.

RÉSUMÉ
Des travaux de terrain ont été réalisés à Salluit au Nunavik (Canada) pour étudier les conditions du pergélisol et cartographier les zones pergélisolées dont le comportement à long terme serait adéquat pour le développement du village malgré le réchauffement climatique prédit lors du prochain siècle. Des essais de pénétration au cône à taux de pénétration contrôlés ont été effectués dans le pergélisol à des températures aussi basses que -5 °C pour déterminer la cryostratigraphie et le comportement au fluage du pergélisol. Un pergélisol riche en glace près de la surface dans des sédiments marins gélifs et des colluvions, et un pergélisol salin pauvre en glace avec quelques lentilles de glace de ségrégation épaisses à de plus grandes profondeurs ont été pénétrés. Le till au contact avec le socle rocheux sous les sédiments marins a aussi été pénétré de quelques centimètres lors d'un essai. Le taux de pénétration utilisé était de 0,1 cm/s; ce taux correspond à un compromis raisonnable entre les résistances à la pointe du pergélisol très élevées attendues si un taux standard de 2 cm/s était utilisé, d'une part, et les résistances obtenues plus faibles dû au comportement au fluage du pergélisol et le temps beaucoup plus long nécessaire à compléter un essai profond à un taux de 0,1 cm/s, d'autre part. Le pergélisol riche en glace et les lentilles de glace sont caractérisés par une résistance à la pointe supérieure à 20 MPa et un rapport de frottement inférieur à 1% alors que, pour le pergélisol salin pauvre en glace, la résistance à la pointe est près de 20 MPa et le rapport de frottement est supérieur à 1%. Une résistance à la pointe plus élevée que 90 MPa à un taux de pénétration de 0,01 cm/s a été mesurée dans le till gelé. Ce taux très faible était nécessaire pour réduire la charge à la pointe et éviter ainsi d'endommager le pénétromètre et le système de poussée linéaire. Les paramètres de fluage déterminés des essais de fluage sont égaux à 5 pour le pergélisol riche en glace et supérieurs à 5 pour le pergélisol salin pauvre en glace. Le comportement au fluage du pergélisol est directement relié au contenu en glace. L'essai de pénétration au cône s'avère un outil géotechnique très utile pour déterminer la cryostratigraphie et le comportement au fluage du pergélisol afin de concevoir des fondations dans les environnements pergélisolés sensibles au réchauffement climatique.

1. INTRODUCTION

The village of Salluit is located in the continuous permafrost zone along the southern shore of Hudson Strait, in Nunavik, Canada (inset of Figure 1). It is a community of about 1100 people characterized by a fast population growth; 60% of the population being under the age of 25. The village lies in the bottom of a restricted valley and most village infrastructures are built on frozen saline and ice-rich marine sediments creating problematic ground conditions for infrastructures construction. The available terrain with proper ground conditions for stable foundation is scarce and the permafrost conditions are poorly known.

For satisfying the fast population growth, a housing development in an open and fairly flat area developed without any in-depth knowledge of permafrost conditions was in progress until recently. However, an active layer detachment failure of about 4000 m^2 occurred in the valley on September 1998; the warmest summer ever recorded in Nunavik. It took place also partially in the gravel road leading to the housing development forcing the moving of twenty houses back to the main community and the abandonment of the development. This superficial failure occurred during a period of climate warming that is well documented in Nunavik since 1993. Several other scars of past active layer detachment failure are also visible in the valley. Proper assessment of available terrain for the village expansion, and housing and utilities development in the valley taking into account the permafrost conditions and the sensitivity of ice-rich permafrost to climate warming is therefore a major concern for Salluit.

Following the request of the government of Québec and the Salluit community itself, a thorough survey for mapping the permafrost conditions at a very large scale (1:2000) was carried out in summers 2002 and 2003. An integrated multi-technique approach was adopted for properly assessing all the soil types, permafrost conditions and lateral changes in conditions and stratigraphy. The techniques used in the field were drilling and sampling of permafrost, penetration-rate controlled Cone Penetration Tests (CPTs) for stratigraphic profiling and studying the creep behaviour of permafrost, and geophysical surveys.

The results and interpretation of the cone penetration tests carried out in the valley of Salluit in relation to the sampling of permafrost are presented in this paper.

2. QUATERNARY GEOLOGY AND PERMAFROST CONDITIONS

According to Gray *et al*. (1993), the region of Salluit was deglaciated by 8600-8700 BP. Simultaneously to the deglaciation, the d'Iberville Sea inundated the land at elevations below the actual marine limit at 150 m. Frost-susceptible marine sediments were then deposited in the basins and overlaid a veneer of till of metric thickness. Very fast at the beginning, the rate of land emergence decreased slowly to the present-day rate of about 2-4 mm/year. Scattered areas in the valley of Salluit are on solid ground made of bedrock, till, glacio-fluvial sand and gravel, and deltaic sand (Figure 1). An important area in the valley is covered by colluvium made of a sequence of peat layers and silty clay coming from the erosion by running water of marine sediments and till covering the valley slope

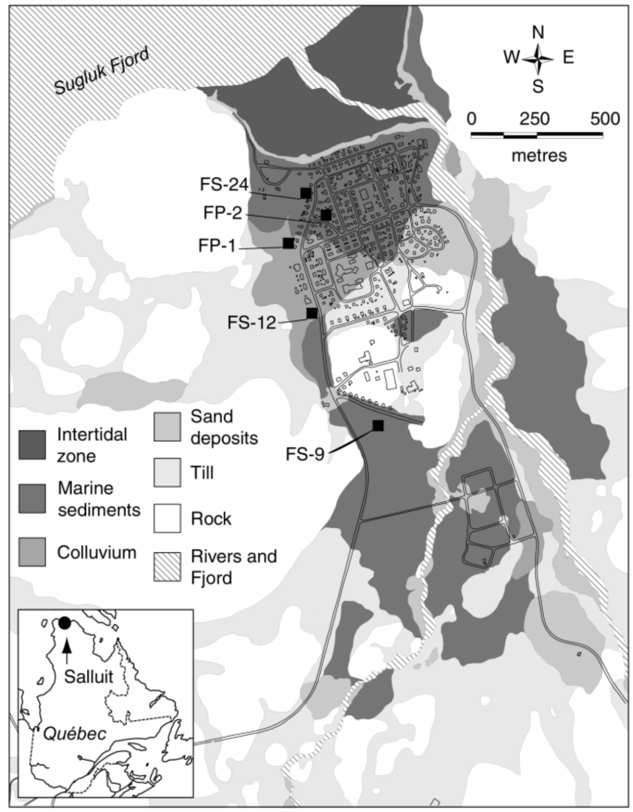

Figure 1. Map of Quaternary deposits in the valley of Salluit. Location of shallow sampling and cone penetration test (FS-#), and deep sampling (FP-#) in permafrost. Inset: location of Salluit in Québec.

The permafrost conditions in the valley of Salluit are highly variable both laterally and vertically following the complex post-glacial history of the valley (Figure 1). Ice-poor permafrost is present in coarse-grained sediments such as sands, gravels and till. These deposits are thaw stable and offer good ground conditions for civil infrastructures. However, aggradational ground ice is found near the permafrost table in marine sediments in the valley uphill (site FS-9 in Figure 1) making an ice-rich permafrost layer few decimetres thick. Aggradational ice is not present in the upper part of permafrost in the marine sediments located in the valley downhill (sites FS-24 and FP-2 in Figure 1). Deeper in the marine sediments, the permafrost is saline ice-poor with few thick lenses of segregated ice. Forming during the sedimentary accumulation, syngenetic ice-rich permafrost is found in the colluvium (sites FS-12 and FP-1 in Figure 1).

The permafrost conditions in the marine sediments and colluvium covering almost two thirds of the valley area are therefore problematic since, following the climate warming predicted for the next century, these superficial ice-rich layers will thaw first and induce differential thaw settlement affecting the performance of civil infrastructures.

3. PENETRATION-RATE CONTROLLED CONE PENETRATION TESTS

Stratigraphic profiling and creep tests with the penetration-rate controlled system (Figure 2) developed at the Centre d'études nordiques of Laval University were carried out in three sites in the valley of Salluit (sites FS-9, FS-12 and FS-24 in Figure 1). This system, that makes use of a linear pushing system applying an actuator technology, is described in details in Buteau *et al*. (in press).

Stratigraphic profiling is a quasi-static CPT performed at a constant rate of penetration providing the stratigraphic logs of permafrost in terms of the variation with depth of cone resistance, friction ratio, temperature and electrical resistivity measured during the CPT. The rate of penetration used was 0.1 cm/s; it is a good compromise between the very high values of cone resistance expected for permafrost at a standard rate of 2 cm/s due to the creep behaviour of ice in permafrost, on one side, and the lower values of cone resistance and the very long time needed for performing deep CTPs at a rate of 0.1 cm/s, on the other side.

The creep test consists of a series of quasi-static CPTs at incremental rates of penetration carried out in a homogeneous permafrost layer. The penetrometer is first driven down to a given depth at a rate of penetration of 0.1 cm/s and then pulled up just enough to unload the tip at no more than a few hundreds of kPa. Several incremental rates of penetration from 0.0001 to 0.06 cm/s are then used to perform the creep test. Each applied rate of penetration is kept constant as long as the cone resistance doesn't reach a constant value. Once this state has been reached and the frozen soil strength is fully mobilized, the rate of penetration is increased to the next step. From this incremental penetration rate-controlled CPT, the creep behaviour of permafrost is evaluated according to the following relationship between the cone resistance and the applied rate of penetration (Ladanyi, 1976):

$$q_c = q_{co}\left(\nu/\nu_o\right)^{1/n} \quad [1]$$

where n is the creep exponent, obtained from the slope of the straight line of the cone resistance q_c as a function of the rate of penetration ν in a double logarithmic plot, while q_{co} is the reference cone resistance at the reference rate of penetration ν_o equal to 0.001 cm/s. This relationship is normally considered to directly reflect the strain rate sensitivity of frozen soil strength at a representative strain rate (Ladanyi, 1972).

3.1 Stratigraphic profiling

Three examples of stratigraphic profiling in permafrost are shown below in Figures 3, 5 and 7 for the study sites FS-9, FS-12 and FS-24 respectively. For each CPT, vertical logs of cone resistance, friction ratio, temperature, electrical resistivity and penetrometer inclination as a function of depth are given. The interpretation and correlation of the first four logs are presented as a stratigraphic column on the graphs.

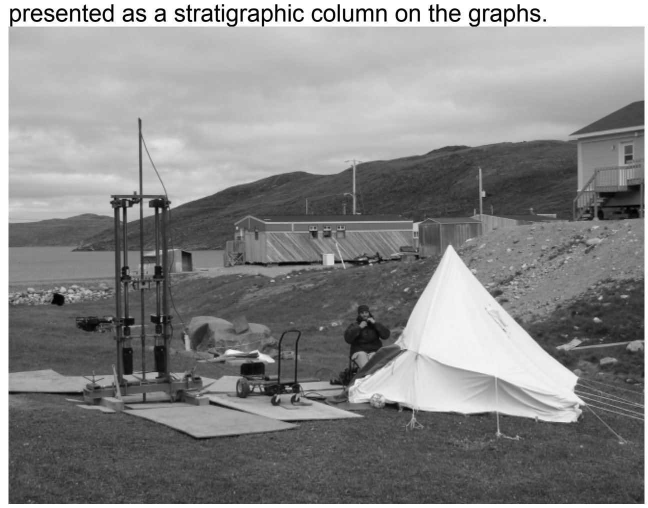

Figure 2. Photograph of field layout of CPT in site FS-24.

Two curves appear in the temperature log. The full line is the quasi-static temperature measured during a CPT while the dashed line with x symbols is the temperature log at equilibrium measured with a thermistor probe lowered in a plastic casing filled with silicone oil (sites FS-9 and FS-12, Figures 3 and 5 respectively) or along a thermistor cable permanently installed in a plastic casing also filled with silicone oil (site FP-2 near site FS-24 for comparison with the CPT carried out in site FS-24, Figure 7). The quasi-static temperature is always higher than the temperature at equilibrium due to the heat generated by the friction mobilised along the penetrometer shaft. The stopping time needed at each 1-m interval to add a new rod to the set of pushing rods during the CPT is enough to allow the friction heat to dissipate and the quasi-static temperature to decrease close to the temperature at equilibrium. This warming-cooling cycle of the penetrometer give a stairway shape to the quasi-static temperature curve (Figures 3 and 5, less apparent in Figure 7).

At first glance, the variations with depth of cone resistance, friction ratio and electrical resistivity seem very noisy. However, these variations reflect the stratified cryofacies of permafrost characterized by a complex sequence of ice lenses and layers of frozen marine sediments.

3.2 Sampling of permafrost

In addition to the CPTs, shallow and deep sampling of permafrost was carried out. During shallow sampling with a diamond core barrel, the unfrozen water content and ice content of undisturbed permafrost samples were directly measured in the field using a calorimetric method (Fortier *et al.*, 1996). The density and pore water salinity were also measured. Results of these measurements are given in Figure 4 and 6 for the sites FS-9 and FS-12 respectively (the results for the site FS-24 are not given). During deep sampling, only the water content and pore water salinity were measured due to the thermal disturbance induced by the drilling technique (Figure 8 for site FP-2 near site FS-24 for comparison with the CPT carried out in site FS-24).

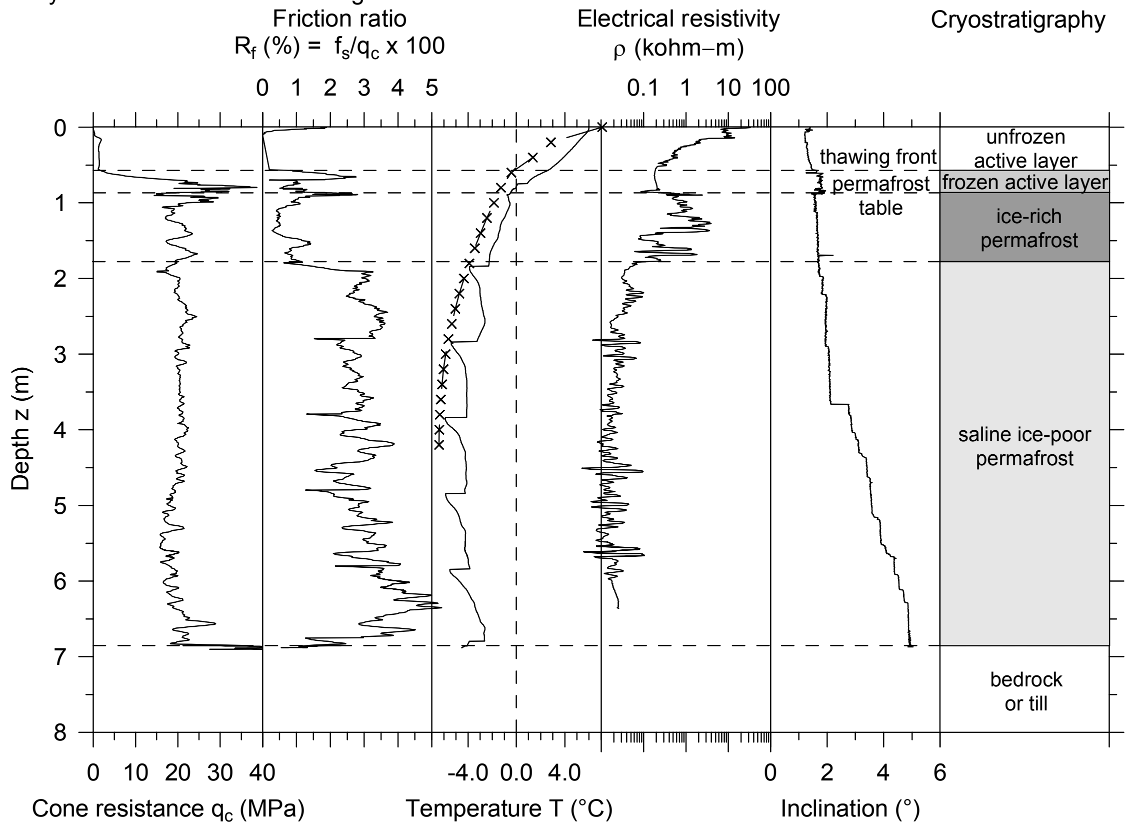

Figure 3. Cone penetration test carried out on July 3rd 2003 in site FS-9 (see Figure 1). Cone resistance, friction ratio, temperature (quasi-static and at equilibrium), electrical resistivity and penetrometer inclination as a function of depth. The cryostratigraphic column is interpreted from the analysis of the CPT results.

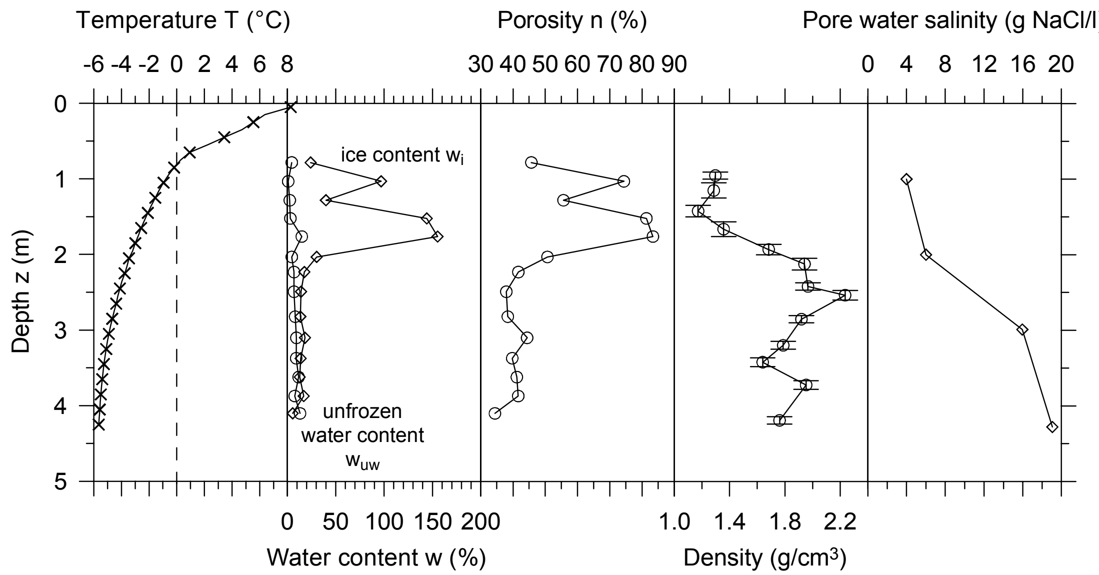

Figure 4. Shallow sampling carried out on July 15th 2002 in site FS-9 (see Figure 1). Temperature, unfrozen water content and ice content, porosity, density and pore water salinity as a function of depth.

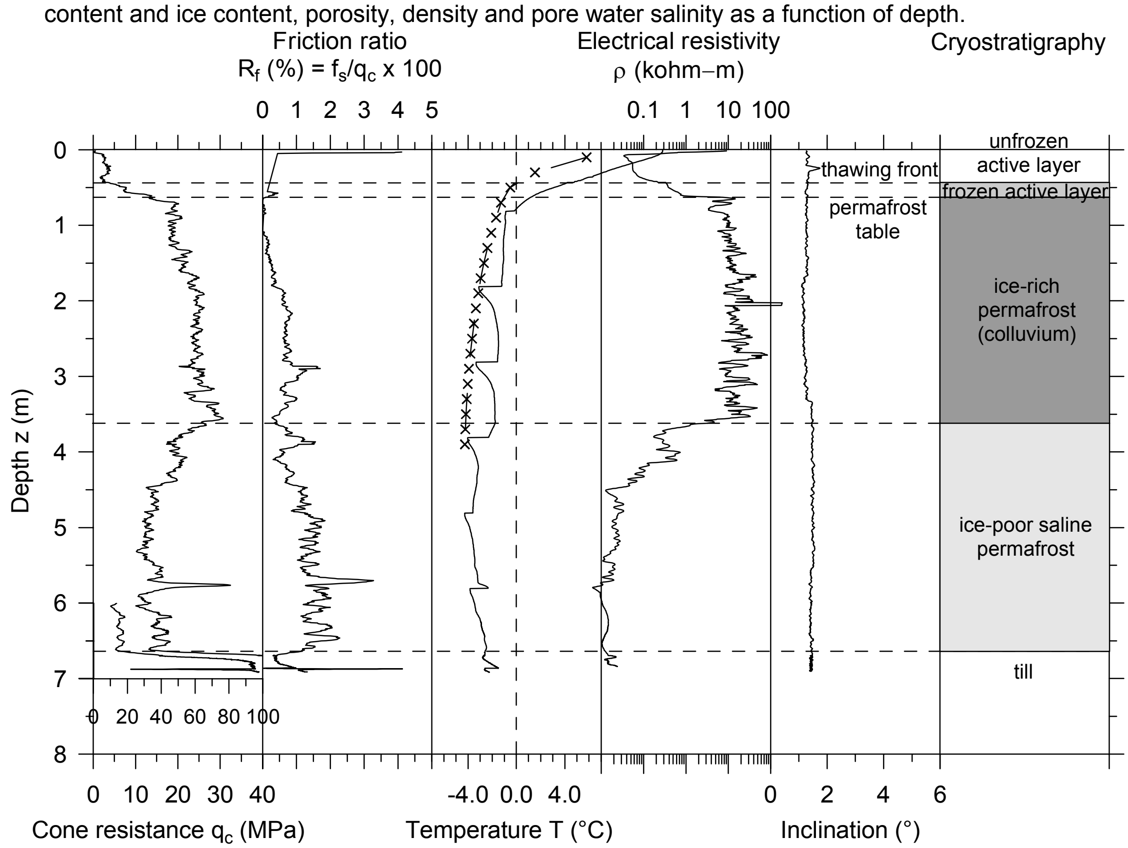

Figure 5. Cone penetration test carried out on June 29th 2003 in site FS-12 (see Figure 1). Cone resistance, friction ratio, temperature (quasi-static and at equilibrium), electrical resistivity and penetrometer inclination as a function of depth. The cryostratigraphic column is interpreted from the analysis of the CPT results. A second axis for the cone resistance from 0 to 100 MPa is provided to bring to the fore the very high values of cone resistance measured in the till at depths greater than 6.6 m.

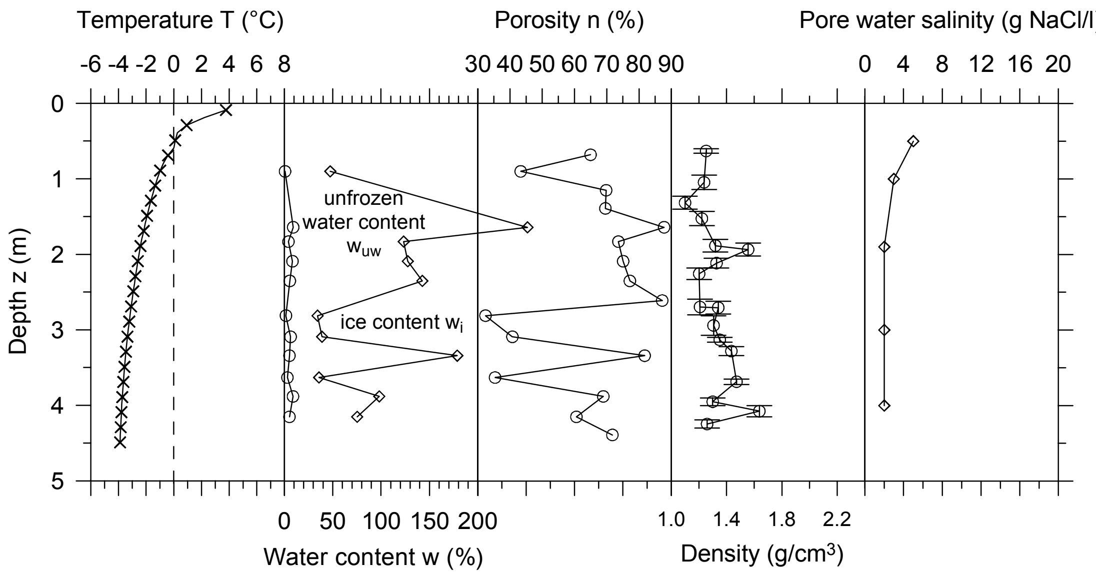

Figure 6. Shallow sampling carried out on July 10th 2002 in site FS-12 (see Figure 1). Temperature, unfrozen water content and ice content, porosity, density and pore water salinity as a function of depth.

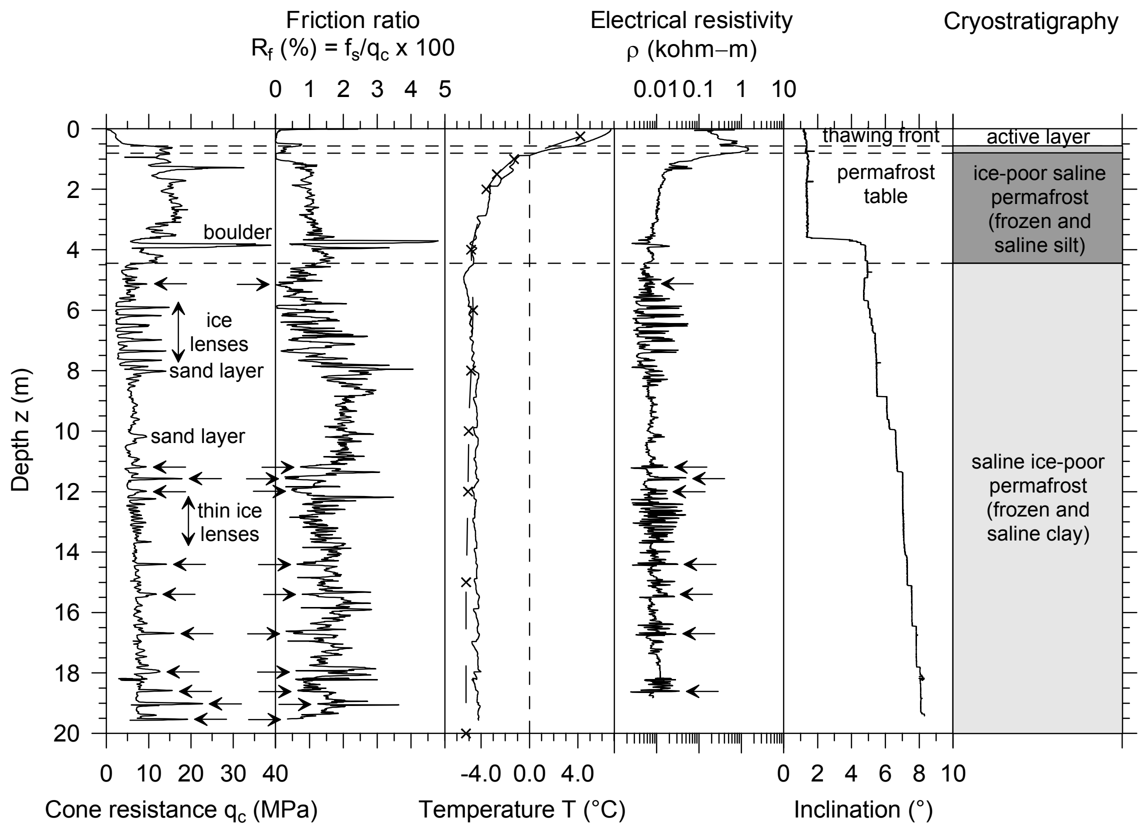

Figure 7. Cone penetration test carried out on July 16th 2003 in site FS-24 (see Figure 1). Cone resistance, friction ratio, temperature (quasi-static and at equilibrium), electrical resistivity and penetrometer inclination as a function of depth. The cryostratigraphic column is interpreted from the analysis of the CPT results. The arrows indicate the location of lenses of segregated ice.

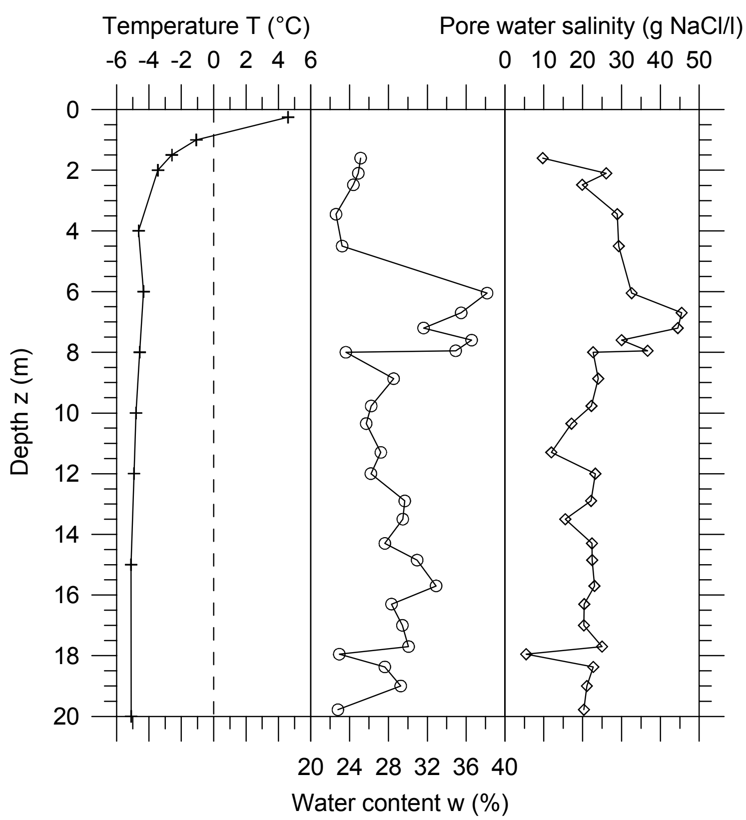

Figure 8. Deep sampling carried out on July 26th and 27th 2002 in site FP-2 (see Figure 1). Temperature, water content and pore water salinity as a function of depth.

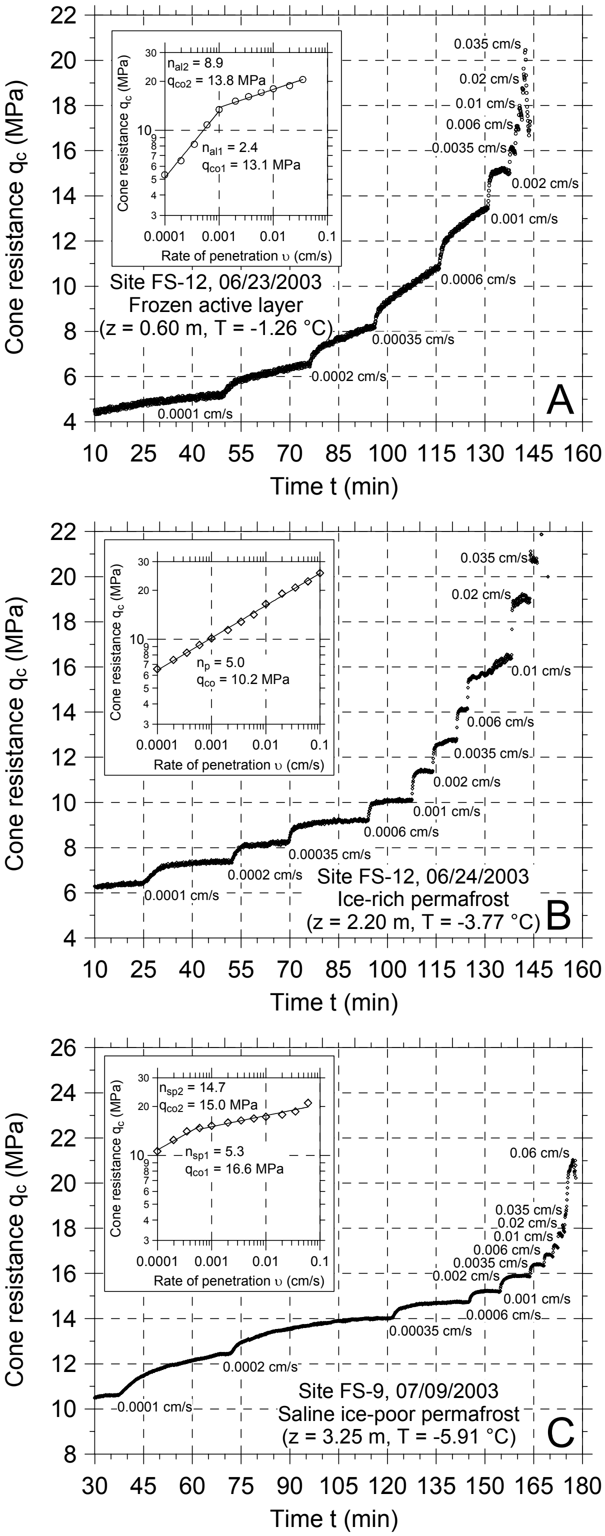

Figure 9. Creep tests carried out in the A) frozen active layer, B) ice-rich permafrost and C) ice-poor saline permafrost. Insets: stabilised cone resistance as a function of rate of penetration for assessing the creep behaviour of frozen ground.

3.3 Creep tests

Three examples of creep test performed in the frozen active layer (site FS-12), ice-rich permafrost (site FS-12) and saline ice-poor permafrost (site FS-9) are shown on Figures 9A, 9B and 9C respectively. For each creep test, the cone resistance as a function of time is given for up to twelve incremental rates of penetration from 0.0001 to 0.06 cm/s. The time needed to reach the full mobilisation of the permafrost strength at a new incremental rate of penetration decreases as the rate of penetration increases. This full mobilisation is reached when the cone resistance stabilises at a given level. This stabilisation is clearly reached at each incremental rate of penetration in Figures 8B and 8C. At that point, the state of dynamic stress-strain in front and on the sides of the cone tip is then stabilised.

In the inset of Figures 9A, 9B and 9C, the relationship between the stabilised cone resistance and the applied rate of penetration on a double logarithmic plot is also shown. The values of creep exponent n and reference cone resistance q_{co} are also given.

4. DISCUSSION

4.1 Stratigraphic profiling

As a general rule of interpretation of a CPT carried out in the permafrost at a rate of penetration of 0.1 cm/s, an ice lens produces very high values of cone resistance in excess of or close to 20 MPa, low friction ratio below 1%, (Buteau *et al.*, in press) and values of electrical resistivity higher than the average value found for the penetrated formation. The low friction in ice-rich permafrost is due to the ice melting under the high stress induced by the cone penetration and the formation of a thin water film around the penetrometer shaft decreasing the friction mobilized along the friction sleeve (Campanella *et al.*, 1984). If the ice lenses or the layers of ice-rich permafrost are thick enough to surround entirely the resistivity module a few decimetres long during the cone penetration, the values of electrical resistivity can be as high as few kohm-m. The layers of frozen marine sediments are characterized by lower values of cone resistance than the ones of ice lenses and values in friction ratio over 1%. Stiff frozen sand beds can also produce very high values of cone resistance but the friction ratio is higher than 1%. The simultaneous correlation on logs of cone resistance, friction ratio and electrical resistivity is therefore needed to discriminate the ice lenses and ice-rich permafrost from the frozen fine sediments and the sand layers.

4.1.1 Site FS-9, permafrost in marine sediments

Five different layers are defined from the CPT performed at site FS-9 (Figure 3). A sharp increase in cone resistance and friction ratio locates the thawing front in the active layer at a depth of 0.6 m. The frozen active layer has variable cone resistance and friction ratio while the superficial unfrozen active layer has very low cone resistance and friction ratio. The decrease in electrical resistivity with depth in the unfrozen active layer is due to the variation in water content from dry conditions in surface to wet conditions in depth. The permafrost table at the 0.9 m depth shows by an increase in electrical resistivity from 0.2 kohm-m in the frozen active layer up to 1 kohm-m in permafrost. This permafrost layer has a large content in aggradationnal ice. It is 0.8 m thick and has an ice content over 50% (Figure 4). At depths larger than 1.7 m marked by a decrease in electrical resistivity to values below 0.1 kohm-m and an increase in friction ratio up to 2%, the permafrost conditions change to a layer of saline ice-poor permafrost with pore water salinity in excess of 16 g NaCl/l (Figure 4). Even if they were observed during the permafrost sampling, the ice lenses in saline ice-poor permafrost were too thin to be detected with the CPT, except maybe on the log of electrical resistivity. The CPT was stopped on refusal at a depth of 6.9 m on the contact with the till or bedrock.

4.1.2 Site FS-12, permafrost in colluvium

Site FS-12 is also made of five different layers (Figure 5). The ice-rich permafrost in colluvium is well delineated by a cone resistance higher than 20 MPa, a friction ratio lower than 1% and an electrical resistivity of about 10 kohm-m while the saline ice-poor permafrost in marine sediments has values close to 15 MPa, higher than 1% and lower than 0.1 kohm-m respectively. The ice-rich permafrost has variable ice content in excess of 40% and pore water salinity less than 4 g NaCl/l (Figure 6). The frozen till at 6.6 m with a cone resistance close to 100 MPa was also penetrated over a few centimetres. The CPT was stopped at a depth of 6.92 m to avoid any damages to the CPT system.

4.1.3 Site FS-24, permafrost in marine sediments

Two layers of saline ice-poor permafrost in depth are defined in site FS-24 (Figure 7). The first layer between 0.9 and 4.4 m in depth is more resistive than the second layer at depths larger than 4.4 m maybe because the salt dissolved in the pore water was leached in the superficial layer or the marine sediments in the first layer are coarser than the ones in the second layer. Numerous thin lenses of segregated ice of centimetric thickness are identified in the second layer of saline ice-poor permafrost. Between 6 and 8 m in depth, a series of ice lenses were penetrated (Figure 7). Ices lenses at these depths were also recovered during the deep sampling in site FP-2 near the site FS-24 (Figure 8). The water content at these depths is higher than 34% in comparison to less than 32% above and below. The pore water salinity is in excess of 20 g NaCl/l. A dropstone was hit at a depth of 3.8 m inducing a sharp increase in penetrometer inclination.

4.2 Creep tests

As observed by Buteau *et al*. (in press) and Ladanyi (1985), a slope change in the creep behaviour is noticeable at a rate of penetration of 0.001 cm/s in the active layer and saline ice-poor permafrost (Figures 9A and 9B). However, this change in creep behaviour is only observed in ice-poor conditions. This bi-linearity of the strain rate sensitivity of frozen ground strength is probably due to the passage from ductile to brittle behaviour of the ice (Ladanyi and Huneault, 1989). The creep exponents are equal to 5 for the ice-rich permafrost and higher than 5 for the saline ice-poor permafrost. At a reference rate of penetration of 0.001 cm/s, the reference cone resistance is higher in saline ice-poor permafrost (16.6 and 15.0 MPa) than the one in ice-rich permafrost (10.2 MPa). The variation in ice content can explain the difference in creep behaviour of permafrost.

5. CONCLUSIONS

The cone penetration test is a useful geotechnical tool to assess the cryostratigraphy and creep beahviour of permafrost for designing foundations in a permafrost environment sensitive to climate warming.

6. ACKNOWLEDGEMENTS

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